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PARAMETRIC STUDY OF THE MINIMUM REQUIRED REINFORCEMENT FOR CRACKING CONTROL IN THICK RESTRAINED RC MEMBERS BASED ON THERMO-HYGRO-MECHANICAL FE ANALYSES

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Abstract

This paper discusses the structural behaviour of walls or slab-like reinforced concrete (RC) elements fully restrained at their ends, considering the effects of self-induced deformations due to the heat of hydration and concrete shrinkage. It focuses on the formation and propagation of cracks in thick ties. The analysed thicknesses are 500 mm and 1000 mm. The ultimate objective of the analyses presented in the paper is the rational calculation of the minimum required area of reinforcement to control cracking. For that purpose, thermo-hygro-mechanical analyses are conducted, so that the non-uniform cross-sectional distribution of self-induced deformations is conveniently simulated, and the crack propagation process can be studied. A staggered analysis approach is followed: an uncoupled thermo-hygral analysis is firstly conducted to calculate the self-induced deformation, in each location throughout the structure thickness, for each instant of time. Then, this deformation field is used as input for the mechanical analysis, where the relevant features of the mechanical concrete behaviour are simulated: maturity; creep; softening behaviour after cracking; and nonlinear bond stress-slip relationship at the steel-concrete interface. The results are discussed in view of the regulatory framework of Eurocode 2 for minimum reinforcement for adequate crack width control.

1. Introduction

The definition of the reinforcement for thick RC slabs or walls is frequently governed by cracking control criteria, particularly in situations where the deformation of such members is externally restrained. Design codes, such as the Eurocode 2 [1], provide simple design procedures for calculation of the required reinforcement. These procedures are simple to use, but involve very important simplifications of the actual structural and material behaviour. One of the most important is the assumption of uniform strains and stresses throughout the member thickness. In the reality, these stresses are not actually uniform. To take such non-uniformity into account, design codes adopt a simple correction factor which is a function of a single variable: the concrete thickness. This simplification is very convenient for a rapid estimate of the required reinforcement. However, the simplicity comes with a price: the calculated amount of reinforcement may give rise to crack openings significantly higher or smaller than the specified crack limit (to meet durability, water tightness or other conditions). In view of these limitations of the design rules, alternative methodologies have been proposed for crack width control, namely the deformation compatibility approach [2].

In this context, this paper shows the experience gained with the application of a thermo-hygro-mechanical framework to the calculation of minimum required reinforcement in thick restrained RC members (slabs or walls). The temperature and shrinkage deformations of concrete are completely hindered at the member extremities, thus creating a case of full end restraint. No additional action is considered.

An uncoupled analysis strategy is followed. The local concrete deformations due to temperature variations during the cement hydration and drying shrinkage are calculated for unidirectional fluxes of temperature and humidity (perpendicular to the middle plane of the studied member). The evolution along time of the temperature and humidity fields, as well as the relationship between humidity and local shrinkage, are determined for a concrete mix and exposure conditions previously characterized in laboratory. Thermo-hygral analyses are carried out using the modelling framework described in [3, 4]. Their output is used as input for the mechanical model. In the mechanical analyses, concrete is discretized using plane stress finite elements (FEs). The constitutive model for concrete is based on a total strain approach with rotating cracks. A Kelvin chain approach is used to simulate creep and the time variation of the concrete modulus of elasticity. The reinforcement is discretized using truss elements. The bond action between steel and concrete is explicitly modelled. The mechanical analyses are made with recourse to the FE package DIANA [5].

The discussion of the analysis results focuses on the mechanical response of the structure in terms of crack propagation, crack openings and steel stresses.

2. Structures under analysis

2.1 Geometry and loading

The analysed structures are RC tie elements, 500 mm and 1000 mm thick. The longitudinal deformation of each tie is fully restrained at its extremities, since the instant of casting. The ties are assumed to be moulded and cured for a period of 7 days after casting. No additional load is considered besides the self-induced deformations due to the heat of hydration and the shrinkage of concrete.

The concrete cover to the longitudinal reinforcement is 50 mm (measured from the concrete surface to the reinforcement axis). For each concrete geometry, two different amounts of reinforcement are considered in the analyses shown in this paper:

- The minimum amount of reinforcement which, according to the Eurocode 2 [1] is required to avoid yielding of the reinforcement, herein labelled as $a_{s,min}$. It is equal to 24.9 cm^2/m for the 0.5 m thick slab and 37,3 cm^2/m for the one with a thickness of

1 m. Note that this is, according to the code, the minimum amount to avoid yielding. The reinforcement which ensures, according to the code, that a certain limit crack opening (e.g. 0.3 mm) is not exceeded is much higher.

- An amount of reinforcement 30% higher than $a_{s,min}$, labelled as 1.3 $a_{s,min}$.

The bar diameter is determined, for all of the analysed geometries, by considering that the bar spacing is equal to 100 mm.

2.2 Finite element modelling

Eight-node plane stress quadrilateral FEs, with 25 mm edges, are adopted to discretize the concrete elements. Compatible interface FEs and truss FEs were used to model the bond action and the steel behaviour, respectively. The model length, (*L* in Fig. 1) is 4 m for the 1 m thick slab. For the 0.5 m thick one, different *L* values were considered (4 m and 2 m), in order to assess the influence of this variable. Only half of the thickness was discretized owing to symmetry.

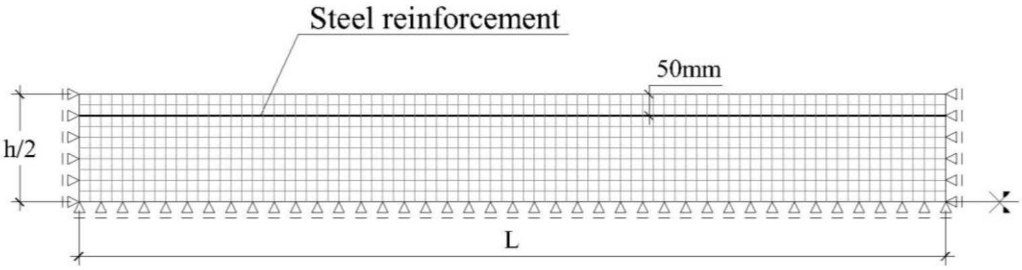


Figure 1: FE mesh for 500 mm thick RC ties

2.3 Material and boundary properties

The parameters to define the concrete properties, the environment and the boundaries take the values previously characterized and experimentally validated [6]. The most relevant parameters are shown in Tab. 1. A full characterization can be found in reference [6]. Note that, to make it concise, no information about the heat generation function is shown in Tab. 1. The adopted concrete mix can be considered as a relatively typical mixture for applications with normal strength requirements. It includes 280 kg/m^3 of CEM II 42.5R, 40 kg/m^3 of fly ash, 143 kg/m^3 of water, 6 kg/m^3 of water reducing admixture and granitic aggregates. The local relationship between the relative humidity in concrete and the local concrete shrinkage strain is given by the equation proposed by Kwak [7], with a shrinkage strain of 539 μ when the concrete humidity reaches 60%. The kelvin chain model to describe the viscoelastic concrete behaviour is fitted to the fib Model Code [8] creep and modulus of elasticity models, considering that the mechanical properties start developing in concrete at the end of the dormant period. The tension softening model adopted for concrete is the one proposed by the fib Model Code [8].

A linear elastic-perfectly plastic behaviour is assumed for steel, with a modulus of elasticity of 200 GPa and a yield stress equal to 500 MPa. The steel-concrete interface behaviour is modelled according to the cubic function by Dörr [9] up to a slip value of 0.06 mm. For higher slip values, the bond-stress is kept constant and equal to 1.9 times the concrete tensile strength ($1.9 \times 2.9 = 5.51$ MPa).

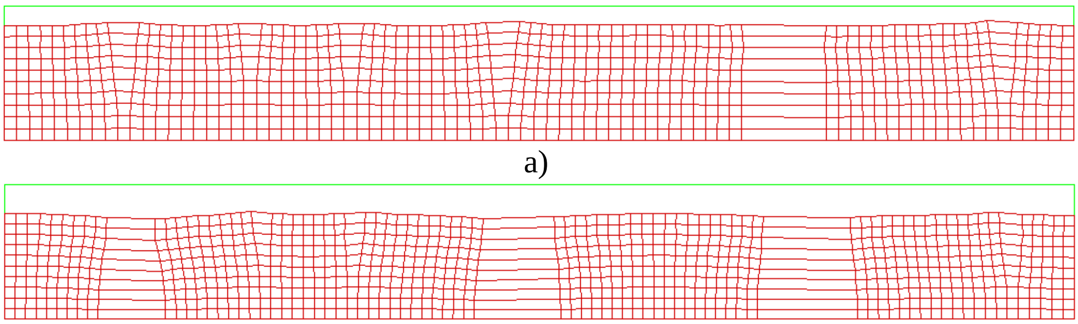
Table 1: Material and boundary properties.

Analysis	**Property**	**Value**
Thermal	volumetric specific heat	2400 $kJm^{-3}K^{-1}$
	thermal conductivity	2.6 $Wm^{-1}K^{-1}$
	convection/radiation coefficient for free surfaces	10.0 $Wm^{-2}K^{-1}$
	convection/radiation coefficient before demoulding	5.0 $Wm^{-2}K^{-1}$
	environmental temperature	20 ºC
Hygral	diffusivity for H=1, D_1	3.08×10^{-10} m^2s^{-1}
	diffusivity for H=0, D_0	0.0967 D_1
	H for D_H = 0.5 D_1	0.8
	material parameter n	2
	moisture emissivity coefficient	4.81×10^{-8} ms^{-1}
	environmental relative humidity	60 %.
Mechanical	average tensile strength	2.9 MPa
	average compressive strength	38 MPa
	fracture energy	0.140 kNm/m^2
	thermal dilation coefficient	10^{-5} $ºC^{-1}$

3. Results and discussion

As mentioned before, the discussion focuses on the results of the mechanical analyses. It was found that the adopted analysis strategy to model cracking and bond action is robust. Converged results were always reached. Preliminary parametric analyses (considering linear or, alternatively, bilinear tension softening models; different structure lengths; and one or, alternatively, three structure spots with 5% lower tensile strength to induce the first crack localizations) showed that the most significant analysis variables (maximum crack openings and steel stresses) are not significantly affected by these variations. This conclusion shows that the analysis results are meaningful.

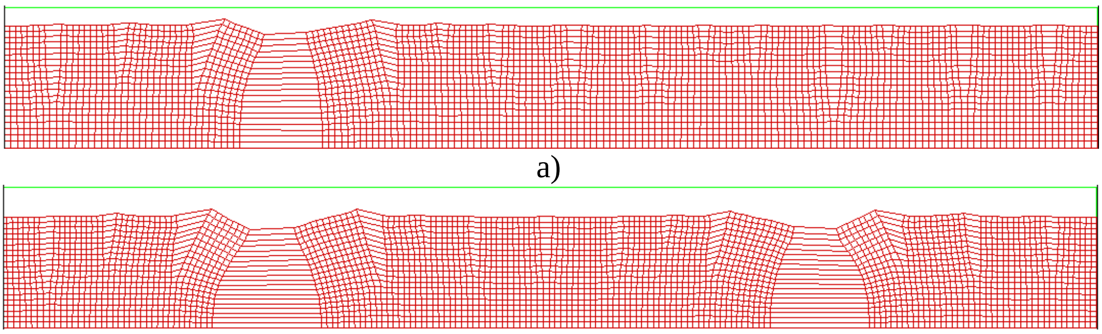
Figs. 2 and 3 show the deformed meshes, for the two concrete thicknesses, for two instants of time: before the formation of the second crack, which is the instant when the highest steel stresses and crack openings are reached; at the end of the analysis. The crack propagation sequence followed the expected behaviour for thick RC elements: initially, micro-cracks were formed throughout all the surface region of the member; then, closely spaced cracks were formed from the surface; later, through cracks were formed, gradually along time. The time variation of steel stresses at the location of the first through crack (the position where the highest stresses occur) is shown in Fig. 4.



a)

b)

Figure 2: Deformed mesh for 500 mm thick RC ties with reinforcement $a_{s,min}$:
a) 3 years after casting; b) at 50 years



a)

b)

Figure 3: Deformed mesh for 1000 mm thick RC ties with reinforcement $a_{s,min}$:
a) 10 years after casting; b) at 50 years

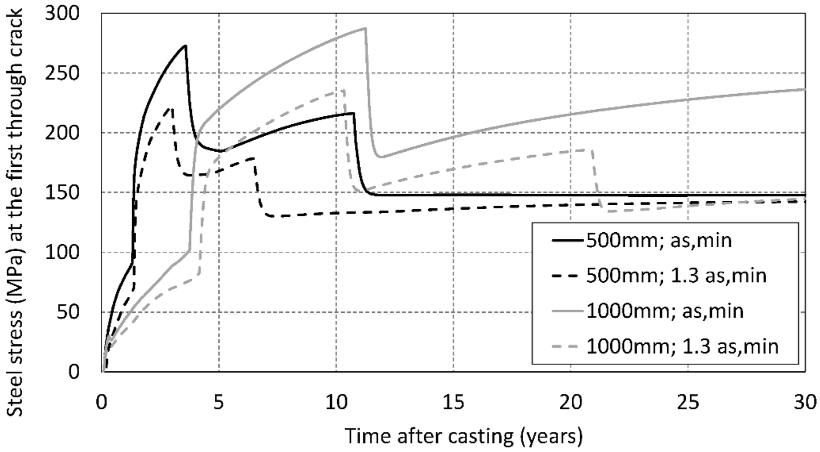


Figure 4: Steel stresses at the most critical position

4. Final remarks

Three relevant conclusions are summarized: (*i*) The analysis results revealed that the rules in Eurocode 2 for calculation of the minimum reinforcement to avoid yielding are too conservative. The maximum steel stress in the analysed ties was always lower than 300 MPa, a value considerably inferior to the yield limit (500 MPa in this case); (*ii*) By adopting an amount of reinforcement 30% higher than $a_{s,min}$, the maximum crack opening was approximately equal to 0.30 mm. According to the Eurocode 2, the required area of reinforcement to reach such limit crack opening is much higher ($\sim$ twice $a_{s,min}$); (*iii*) the adopted analysis strategy can be a useful tool to study the cracking behaviour of thick RC members.

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